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Heat and Moisture Production Rates of a Modern U.S. Swine Breeding, Gestation, and Farrowing Facility

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HEAT AND MOISTURE PRODUCTION RATES OF A MODERN U.S. SWINE BREEDING, GESTATION, AND FARROWING FACILITY

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ABSTRACT. *Current recommendations for swine building ventilation system design to maintain an environment conducive to animal productivity and well-being are based on heat and moisture production rates measured in the 1950s and 1970s. Advancements in animal genetics, nutrition, and management practices to increase productivity and pork quality since then have led to considerable changes in heat and moisture production rates of modern swine and their housing systems. This study quantifies the total heat production rate (THP) of the animals, which is partitioned into house-level latent heat or moisture production rate (LHP, MP) and house-level sensible heat production rate (SHP), of a 4300-sow breeding, gestation, and farrowing facility in Iowa for 16 consecutive months. The THP was determined using indirect animal calorimetry, LHP or MP was determined from mass balance, and SHP was calculated as the difference between THP and LHP. A mobile air emission monitoring unit equipped with state-of-the-art gas analyzers and a data acquisition system was used to monitor the deep-pit breeding and early gestation barn [1800 head, 204 ±3.2 kg head^{-1} (mean ±SE)], the deep-pit late gestation barn (1800 head, 219 ±3.0 kg head^{-1}), and two shallow-pit (pull-plug) farrowing rooms (40 sows with litters per room, 223 ±0.4 kg head^{-1}). Results from the study show that THP at 20°C averages 1.89 W kg^{-1} for sows in the breeding and early gestation stage, 1.57 W kg^{-1} for sows in the late gestation stage, and 3.35 W kg^{-1} for sows and litters in week 0 of the lactation stage. The corresponding house-level LHP for the three stages averages 0.74 W kg^{-1} (early gestation), 0.57 W kg^{-1} (late gestation), and 1.98 W kg^{-1} (lactation, week 0). Finally, the corresponding house-level SHP for the three stages averages 1.15 W kg^{-1} (early gestation), 1.00 W kg^{-1} (late gestation), and 1.37 W kg^{-1} (lactation, week 0). Compared with the ASABE Standards, the values from the current study for gestation sows in their early and late pregnancy stages showed increases of 35% and 12% in THP, 72% and 34% in LHP, and 19% and 3% in SHP, respectively. Values for lactating sows and litters during the first week after parturition showed changes of 29% in THP, 52% in LHP, and 6% in SHP relative to the ASABE Standards. The reductions of THP from day to night for the three stages were 30% (early gestation), 27% (late gestation), and 6% (lactation). These data will help with updating the standards for ventilation design and operation of modern swine housing.*

Keywords. *ASABE Standards, Bioenergetics, House-level heat and moisture production, Sows, Ventilation design.*

Maintaining an optimal indoor environment for all stages of swine production is critical to enhance animal well-being and maximize productivity. With the mechanically ventilated barns typically used in swine breeding, gestation, and farrowing facilities, the ventilation system is the primary control of the environmental conditions, including temperature, humidity, and gas concentrations. While ventilation systems in livestock barns provide control of indoor air quality for gas concentrations, design of the ventilation systems is fundamentally based on the heat and moisture production rates (HP and MP) of the animals and their surroundings. Generally, proper indoor air quality will be achieved when the indoor air relative humidity (RH) and temperature are adequately controlled. Therefore, it is critical to have accurate values for both the total heat production rate (THP) of the animals and, more importantly, its partitioning into house-level MP or latent heat production rate (LHP) and house-level sensible heat production rate (SHP). However, the THP, MP, and SHP values used in the current ASABE Standards are from studies conducted in the 1950s and 1970s (Bond et al., 1959; Ota et al., 1975), and modern studies are lacking. Since the Bond et al. (1959) study, only Brown-Brandl et al. (2014) has measured HP and MP of gestating gilts and lactating sows and litters. With remarkable changes in genetics, nutrition/feeding, and production methods (Brown-Brandl et al., 2004), it is prudent to update the THP, MP, and SHP values for swine and their housing systems under modern production practices. Similar measurement work has been conducted for contemporary poultry (Xin et al., 1998, 2001; Chepete and Xin, 2002, 2004; Chepete et al., 2004, 2011; Hayes et al., 2013).

Table 1 shows previous studies quantifying heat produc-

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Table 1. Selected literature values on specific total heat production rate (THP), latent heat production rate (LHP), and sensible heat production rate (SHP) of pigs.

Source	Production Stage	Temperature (°C)	Body Mass (kg)	THP (W kg^{-1})	LHP (W kg^{-1})	SHP (W kg^{-1})
Cairnie and Pullar (1957)	Early weaned pigs	15	4.0	6.4	-	-
		20	4.0	5.2	-	-
		25	4.0	4.5	-	-
Bond et al. (1959)	Lactating sow and litter	15	180	1.6	0.4	1.2
		20	180	1.4	0.4	1.0
		25	180	1.3	0.5	0.8
Ota et al. (1975)	Weaned pigs	29	3.2	3.8	-	-
		29	4.5	3.1	-	-
McCracken et al. (1980)	Early weaned pigs	20	3.3	6.0	-	-
		29	3.3	4.1-5.2	-	-
McCracken and Gray (1984)	Early weaned pigs	25	3.2	5.2	-	-
		25	4.2	4.7	-	-
		25	4.9	4.3	-	-
		23	5.0	4.3	-	-
		23	5.9	4.7	-	-
		23	6.0	4.6	-	-
Harmon et al. (1997)[a]	Early weaned pigs	23.3	4.4	5.6	2.6	3.0
		25.6	4.4	5.1	2.6	2.5
		23.3	6.1	5.8	2.8	3.0
		25.6	6.0	6.0	3.0	3.0
Brown-Brandl et al. (2014)[a]	Gestating gilts	23.5	148	2.95	1.35	1.60
	Gestating gilts	20.7	138	3.04	1.85	1.19
	Preparturition	23.7	183	1.89	1.27	0.62
	Birth today 7	24.7	209	2.55	2.09	0.46
	Day 8 to 14	24.1	222	3.80	1.81	1.99
	Day 15 to 21	24.7	249	3.70	2.03	1.67
	Day 22 to weaning	24.9	283	3.28	1.62	1.66

[a] LHP and SHP values are at room level, i.e., including moisture evaporation from other sources (e.g., manure, urine, spilled water) as well as the animal's latent heat loss.

tion rates for sows and piglets. Bond et al. (1959) measured the HP and MP of five individually housed sows and litters in a calorimeter room that was cleared of manure twice a day, which removes the impact of animal housing and manure storage. While such calorimeter studies are valuable for delineating the animal's HP and MP (bioenergetics), the impact of the housing system or surroundings on the house-level heat and moisture loads must be quantified for practical design and operation of the building ventilation system. Harmon et al. (1997) measured THP, room-level MP, and room-level SHP of early weaned pigs and found increases of 135% in MP and 55% in THP for 4 to 6 kg piglets relative to the current ASABE Standards. Brown-Brandl et al. (2014) measured THP, room-level MP, and room-level SHP of gestating gilts and lactating sows and litters. The gestating gilts had a 122% higher measured THP than the THP values achieved by extrapolating THP curves for growing pigs. The lactating sows and litters had THP values comparable to the ASABE Standards on a unit mass basis, but with 30 kg heavier sows and litters at parturition. Additionally, the documented studies do not provide the diurnal patterns of HP. This could be critical, as HP is closely tied to animal activity and can differ significantly depending on the time of day. This diurnal change in HP will have an impact on the ventilation and supplemental heating needs of the animals. The new THP, MP, and SHP data can also be used to update common design resources, such as the Midwest Plan Service structures and environment handbook (MWPS, 1983a) and the CIGR handbook on climatization of animal houses (CIGR, 2002).

The objective of this study was to quantify THP and its partitioning into house-level LHP and house-level SHP for a Midwestern U.S. swine breeding, gestation, and farrowing facility over 16 consecutive months (February 2012 to June 2013). The diurnal patterns of HP, specifically the differences between daytime and nighttime, were also delineated.

Materials and Methods

Site Description

A 4300-sow (PIC genetics) capacity breeding, gestation, and farrowing facility located in central Iowa was used in this field monitoring study. The facility consisted of two farrowing barns with nine farrowing rooms each, a breeding and early gestation barn, a late gestation barn, and an external above-ground manure storage tank for the farrowing operation. The farrowing rooms (fig. 1) each measured 15.5 m long (L) × 13.9 m wide (W) and used a shallow pull-plug manure pit (0.61 m deep) that was drained after every turn (approx. 21 days) into an external storage tank. Each room had 40 farrowing crates (2.1 m L × 1.5 m W pen; 2.1 m L × 0.61 m W crate) arranged in four rows. Sows were moved into the rooms 2 to 4 days of preparturition. Piglets were typically weaned at 18 to 20 days of age, at which time the rooms were depopulated and cleaned by power washing. One 66,000 W unvented liquid propane (LP) heater provided supplemental heat in each room. Water was supplied through nipple drinkers. The nine rooms in each farrowing building shared a common preheated or precooled (with evaporative pads) hallway that served as the air inlet. Ventilation for each room was provided by two 0.3 m fans, two 0.6 m variable-speed fans, one 0.91 m fan, and one 1.2 m fan.

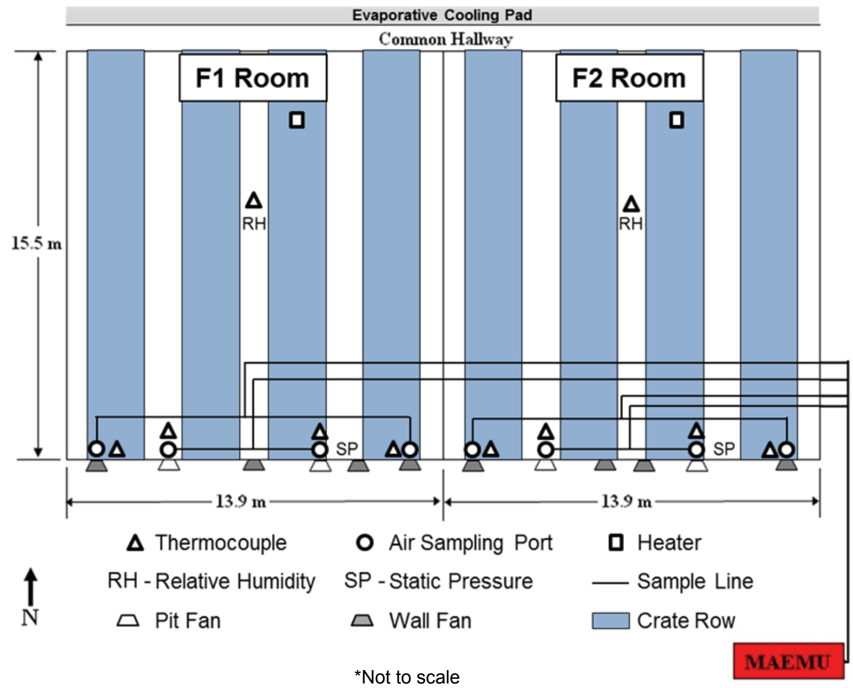


Figure 1. Schematic of F1 and F2 farrowing rooms (not to scale) showing air sampling, temperature, static pressure, and relative humidity measurement locations (MAEMU = mobile air emissions monitoring unit).

The breeding and early gestation barn and the late gestation barn, designated the B/EG and LG barns, respectively, had the same dimensions, ventilation design, and 1800-head capacity each (fig. 2). Sows were housed in the B/EG barn post-weaning until approximately day 40 of gestation (45 to 47 days total in barn). They were then housed in the LG barn until 2 to 4 days of preparturition. In both barns, the sows were housed in individual stalls (2.1 m L × 0.61 m W). Each barn used a deep manure pit (3.05 m in depth) below the fully slatted floor for manure storage. The deep-pit storages were emptied semi-annually, in the fall and spring, through pump-out ports located along the north and south sides of the barns. The east-west oriented barns had dimensions of 121.9 m L × 30.5 m W and used mechanical ventilation year round. Each barn had a total of twelve 0.61 m pit fans, six on the south side and six on the north side, and fifteen 1.37 m fans on the west end walls. The pit fans provided low-stage ventilation, while the wall fans provided tunnel ventilation during warm weather. Bi-flow actuated ceiling inlets were used for lower ventilation stages. Evaporative cooling pads on the east end wall (1.83 m H × 30.5 m W × 15.2 cm D) and in the middle section of each side wall (1.83 m H × 30.5 m W × 15.2 cm D) cooled incoming air during hot weather. Ten 66,000 W unvented LP heaters provided supplemental heat in each barn. Water was supplied through common water troughs that ran the length of the buildings.

The sows were fed a corn-soy ration that was adjusted based on production stage and body condition. For gestating sows, the ration had a metabolic energy (ME) content of 3095 kcal kg^{-1} and a crude protein (CP) content of 21.04%. Gestating sows were fed once per day (07:00 h). Gestating sows with body condition score 1 (skinniest sows) were fed 4.5 kg per day, while sows with condition score 3 (heaviest) were fed 1.8 kg per day. Condition 2 sows were fed 2.3 to 3.2 kg of feed per day depending on gestation status. Once the gestating sows were moved to the farrowing rooms, approximately 2 to 4 days before farrowing, they were fed 1.8 kg per day until farrowing. For lactating sows (post-farrowing), ME content was 3278 kcal kg^{-1} and CP content was 21.14%. Lactating sows were fed four times per day (00:00, 09:00, 12:00, and 18:00 h) with each feeding of up to 3.6 kg for a maximum daily feed intake of 14.5 kg.

Measurement System

A mobile air emissions monitoring unit (MAEMU) was used to continuously collect data on gaseous concentrations, thermal conditions, and operational status of the ventilation fans from the previously described barns and farrowing rooms. A detailed description of the MAEMU and its standard operation protocols can be found in Moody et al. (2008). The MAEMU housed, among other measurement and data acquisition equipment, a photoacoustic multi-gas analyzer (model 1412, Innova AirTech Instruments A/S, Ballerup Denmark) to measure CO_2 concentrations and dewpoint temperature, and a paramagnetic oxygen gas analyzer (model 755A, Rosemount Analytical, Irvine, Cal.) to measure O_2 concentrations. The Innova multi-gas analyzer was challenged weekly against span gases and a zero gas and was recalibrated if not within 5% of the expected values. The Rosemount O_2 analyzer, due to a slight drifting tendency, was challenged and calibrated weekly with a span O_2 gas (20.9% O_2 balanced with N_2) and a zero gas (ultra-high-purity nitrogen gas, 99.999%). A positive-pressure gas sampling system was housed in the MAEMU and was controlled by the data acquisition system (fig. 3). There were 18 total in-barn sample locations, which, when

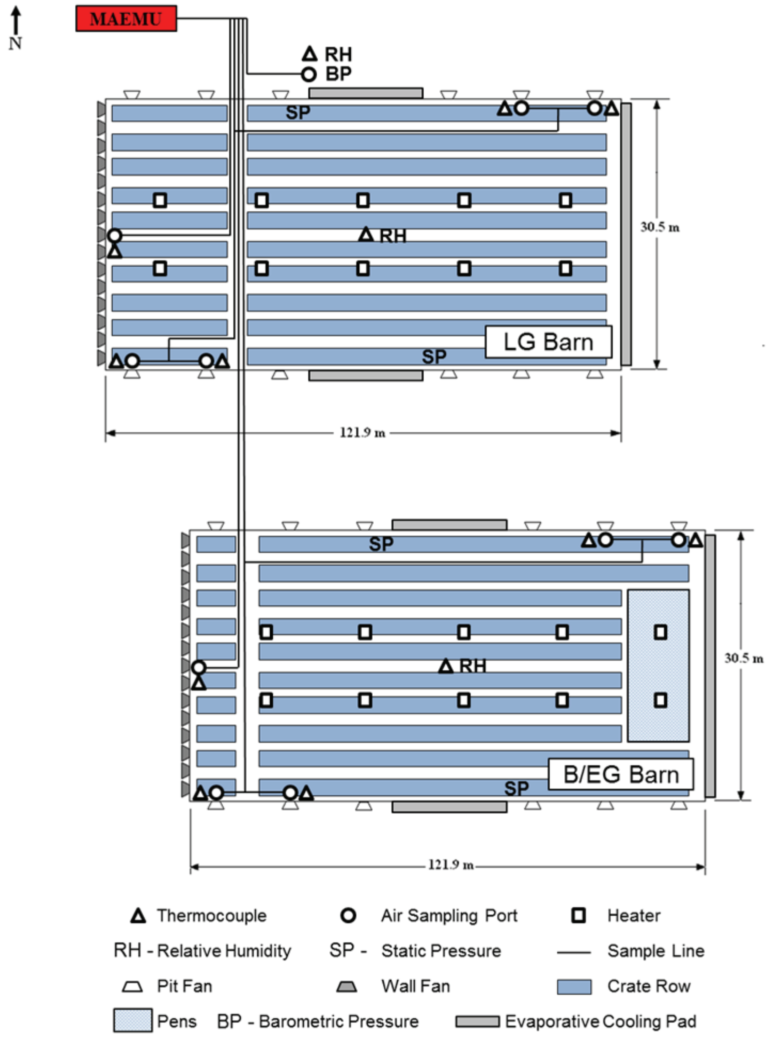
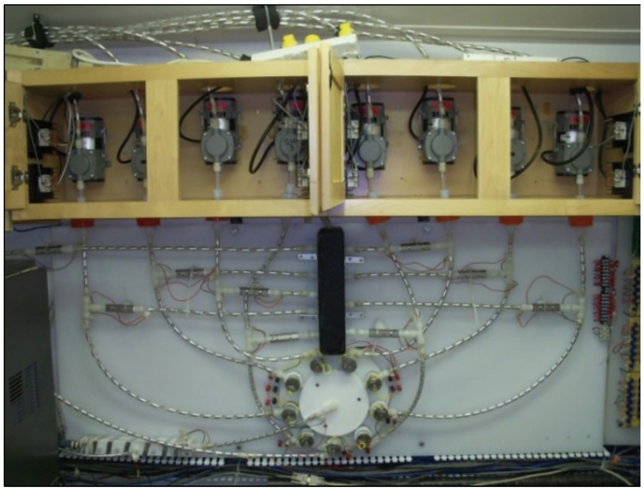


Figure 2. Schematic of breeding and early gestation (B/EG) barn and late gestation (LG) barn (not to scale) showing air sampling, temperature, static pressure, relative humidity, and barometric pressure measurement locations (MAEMU = mobile air emissions monitoring unit).

composited based on barn and fan stage, resulted in eight in-barn samples plus one ambient sample location. Pit fan sampling ports were located below the slatted floor in the deep-pit head space directly under each pit fan in the pump-out accesses. Wall fan sampling ports were located approximately 1.0 m in front of each wall fan. The sample port locations were chosen to represent the exhaust air leaving each barn or room. The sample lines were fluorinated ethylene propylene (FEP) Teflon tubing and were equipped with a dust filter (3011 NAPA, Atlanta, Ga.) and a 47 mm membrane filter (5 to 6 µm, Savillex, Eden Prairie, Minn.) to prevent particles from clogging the tubing or damaging the gas analyzers. All filters, sample lines, and sample pumps were checked weekly for leaks or blockages and addressed as needed. To ensure accurate gas concentration measurement given the analyzer response time, each location was sampled for 8 min, with the first 7.5 min for instrument stabilization and the last 0.5 min readings for measurement. Each in-barn location was sampled sequentially so that a complete round of the barn locations occurred in 64 min. An ambient sample was taken at a less frequent rate (every 128 min) due to the relative stability of its composition.

Selected fans representing each ventilation stage (at least 50% of each stage fans) were calibrated *in situ* at multiple operating (i.e., static pressure) points using a Fan Assessment Numeration System (FANS) (Gates et al., 2004) to develop performance curves. The on/off status of each fan was monitored continuously by an inductive current switch on the fan motor's power cord (Muhlbauer et al., 2011) with its analog output connected to the data acquisition system. The speed of each variable-speed fan was measured by Hall effect speed sensors (GS100701, Cherry Corp., Pleasant Prairie, Wisc.). Static pressure sensors (model 264, Setra, Boxborough, Mass.) were located near the south wall of each farrowing room and near the middle of the north and south walls in the B/EG and LG barns.

Figure 1 shows the monitoring system layout for the farrowing rooms. Two farrowing rooms, designated F1 and F2, were selected for monitoring. The rooms were sampled and monitored identically. A composite air sample was taken by combining samples from each pit fan of each room, and a second composite sample was taken by combining samples from the two lowest-stage wall fans of each room. Figure 2 shows the monitoring system layout for the



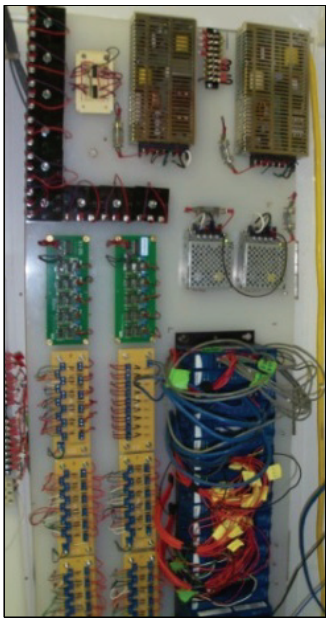


Figure 3. Measurement of gas concentration, dewpoint temperature, thermal environment, and building ventilation: (top) positive-pressure gas sampling system and (bottom) data acquisition system.

B/EG and LG barns. The two barns were sampled and monitored identically. Exhaust air samples of each barn were drawn as a composite from four of the lowest-stage pit fans, with a second sample drawn from the lowest-stage end wall fans. Air temperature, RH, static pressure, fan operation status, heater operation status, O_2 concentration, and barometric pressure were measured and recorded at 1 s intervals. The data were then averaged over 30 s to match the sampling frequency of the Innova analyzer. Heat and moisture production rates were calculated every 30 s and averaged to determine daily time-weighted average (TWA) as well as daytime and nighttime values.

Determination of THP, House-Level MP or LHP, and House-Level SHP

THP of the pigs was determined using the indirect calorimetry technique. Namely, THP is related to O_2 consumption and CO_2 production (for monogastric animals) using the following relationship (Brouwer, 1965):

$$\text{THP} = 16.18\left(\text{O}_2 - \text{O}_{2heater}\right) + 5.02\left(\text{CO}_2 - \text{CO}_{2manure} - \text{CO}_{2heater}\right) \tag{1}$$

$$\text{RQ} = \frac{\left(\text{CO}_2 - \text{CO}_{2manure} - \text{CO}_{2heater}\right)}{\left(\text{O}_2 - \text{O}_{2heater}\right)} \tag{2}$$

where

THP = total heat production rate of the pigs in the building (W)

RQ = respiratory quotient (unitless)

O_2 = total oxygen consumption rate of the barn or room (mL s^{-1})

CO_2 = total carbon dioxide production rate of the barn or room (mL s^{-1})

$CO_{2manure}$ = carbon dioxide production rate of the manure (mL s^{-1})

$CO_{2heater}$, $O_{2heater}$ = carbon dioxide production rate and oxygen consumption rate of the heaters (mL s^{-1}).

The CO_2 production rate of manure was estimated as 2% of the barn or room level CO_2 production based on deep-pit flux chamber measurements and an empty farrowing room with full shallow-pit measurement. The CO_2 production rate of a single heater was determined to be 1268 mL s^{-1} (1924 mL CO_2 per L of LP consumed) from field measurements of an empty, clean farrowing room with a single, running heater. The O_2 consumption rate and MP of the heater were calculated through stoichiometry to be 2323 mL O_2 s^{-1} and 1.37 g H_2O s^{-1} (3225 mL O_2 and 2.08 g H_2O per L of LP consumed), respectively.

The total O_2 consumption rate and CO_2 production rate at the barn or room level were determined from incoming and exhaust O_2 and CO_2 concentrations and the building ventilation rate, with adjustments made for changes in temperature, pressure, moisture content, and air composition (McLean, 1972):

$$\text{O}_2 = \left(\frac{V_o}{\alpha}\right)\left(\left[\text{O}_{2a}\right] - \alpha\left[\text{O}_{2o}\right]\right)\times 10^{-6} \tag{3}$$

$$\text{CO}_2 = \left(\frac{V_o}{\alpha}\right)\left(\alpha\left[\text{CO}_{2o}\right] - \left[\text{CO}_{2a}\right]\right)\times 10^{-6} \tag{4}$$

$$\alpha = \left(\frac{V_o}{V_a}\right) = \frac{1-\left(\left[\text{O}_{2a}\right]+\left[\text{CO}_{2a}\right]\right)\times 10^{-6}}{1-\left(\left[\text{O}_{2o}\right]+\left[\text{CO}_{2o}\right]\right)\times 10^{-6}} \tag{5}$$

where

O_2 = total oxygen consumption rate of the barn or room (mL s^{-1})

CO_2 = total carbon dioxide production rate of the barn or room (mL s^{-1})

$[O_{2o}]$, $[O_{2a}]$ = oxygen concentration at outlet and ambient, respectively (ppm)

$[CO_{2o}]$, $[CO_{2a}]$ = carbon dioxide concentration at outlet and ambient, respectively (ppm)

α = correction factor for the outlet airflow rate

V_o, V_a = ventilation rate at STPD (0°C, 101.325 kPa, dry basis) at outlet and ambient, respectively (mL s^{-1}).

The house-level MP (or LHP), which includes latent heat of the pigs and moisture evaporation from manure and/or water troughs, was calculated with a mass-balance equation:

$$\mathrm{MP} = \rho V_o (W_o - W_a) - \mathrm{MP}_{heater}/1000 \quad (6)$$

$$\mathrm{LHP} = \mathrm{MP} \times h_{fg} \times 1000 \quad (7)$$

where

MP = barn or room level moisture production rate (kg H_2O s^{-1})

W_o, W_a = humidity ration of outlet and ambient air, respectively (kg H_2O kg^{-1} dry air)

ρ = air density of exhaust air (kg m^{-3})

MP_{heater} = moisture production rate of heater (g H_2O s^{-1})

LHP = latent heat production rate at barn or room level (W)

h_{fg} = latent heat of vaporization for water (2427 J g^{-1})

1000 = conversion of MP from kg s^{-1} to g s^{-1}.

The house-level SHP was calculated as the difference between THP and house-level LHP:

$$\mathrm{SHP} = \mathrm{THP} - \mathrm{LHP} \quad (8)$$

The heat and moisture production rates calculated in the above equations are for the entire barn or room and were calculated every 30 s to match the sampling frequency of the Innova analyzer. The values were then averaged by time of day to provide day (06:00-17:00 h) and night (17:00-6:00 h) values. A TWA value was then calculated with equation 9:

$$\mathrm{HP_{TWA}} = \frac{11 \times \mathrm{HP}_D + 13 \times \mathrm{HP}_N}{24} \quad (9)$$

where

$\mathrm{HP_{TWA}}$ = time-weighted average heat production rate (W)

HP_D = average heat production rate during daytime (W)

HP_N = average heat production rate during nighttime (W)

11, 13 = hours in daytime and nighttime periods, respectively (h)

24 = hours in a day (h).

The population of animals in the monitored barns or rooms was recorded by the farm staff and conveyed to the research team. Additionally, sow and piglet weights were collected to allow for calculation of the specific heat and moisture production rates (per kg of body mass). Piglet weights were taken on day 1 or 2 of post-birth and at weaning, with selected litters weighed at 6 d intervals from birth to weaning. This allowed for the development of a piglet growth curve. Sow weights were collected from a group of 75 sows entering farrowing and post-weaning. Selected sows from each parity were also weighed at day 7 and day 14 post-parturition. From these sow weights and piglet weights, curves were developed to span the farrowing and lactation cycle.

For the 16-month monitoring from February 2012 to June 2013, data completeness was defined as having at least 75% of the possible data points collected in a 24 h monitoring period (starting at 00:00 h) meeting the quality control criteria (Moody et al., 2008). Data for a portion of a day might be missing due to instrument maintenance, malfunction, or site activity (e.g., washing down farrowing rooms). Data associated with the time periods that did not meet these completeness criteria were excluded from the analysis. The drifting tendency of the O_2 analyzer and low gas concentration differences between the exhaust and incoming air accounted for a significant portion of the excluded data.

Results and Discussion

For the monitoring duration (February 2012 to June 2013), average daily heat production rates were obtained for 152 days (32% of the monitored days) for the B/EG barn, 174 days (36%) for the LG barn, 167 days (35%) for the F1 room, and 211 days (44%) for the F2 room.

Figure 4 shows the average body mass (BM) of a sow and litter versus day of the farrowing cycle, with day 0 being the day of parturition. Table 2 shows the sow BM in the B/EG and LG barns for each parity. The average BM for each barn was calculated based on the parity distribution provided by the producer. The average BM (and lower and upper limits of 95% CI) of sows was 204 kg (197 and 210) in the B/EG barn and 219 kg (213 and 225) in the LG barn.

HP of B/EG and LG Barns

The diurnal HP patterns for the B/EG and LG barns show a sharp increase in THP, LHP, and SHP at the daily 07:00 h feeding and then a gradual decrease until the workers leave the barns at 16:00 h. Figure 5 shows an example of this pattern for the LG barn. This behavior shows the relationship between animal activity and heat production rate, and how heat production can be affected by management practices such as single-event feeding.

Respiratory quotient (RQ) ranged from 0.81 to 1.3 (fig. 6), with daily means (±SE) of 1.06 (±0.01) for the B/EG barn and 1.04 (±0.01) for the LG barn. Daily mean values for THP, barn-level LHP, and barn-level SHP are shown in figures 7, 8, and 9, respectively, for the B/EG and LG barns. The results from the B/EG and LG barns are summarized in table 3, which includes daytime, nighttime, and TWA values of THP, LHP, and SHP. The results were further divided into temperature categories of 20°C ±2.5°C and 25°C ±2.5°C, comparable with those in the ASABE

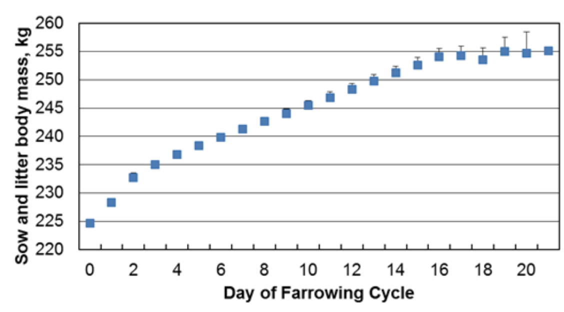


Figure 4. Lactating sow and litter body mass curve during the monitoring period (mean ±SE).

Table 2. Sow body mass (BM, kg sow^{-1}) by parity and average BM based on the parity distribution for the breeding and early gestation (B/EG) and late gestation (LG) barns.

Production Stage	Variable	Parity 0	1	2	3	4	5	≥6	Avg. BM
	Population distribution	8%	22%	20%	18%	13%	10%	9%	
B/EG	BM (kg sow^{-1})	140	179	202	210	231	231	242	204
	SE	6.5	5.8	5.4	12.8	7.3	8.3	10.2	3.2
LG	BM (kg sow^{-1})	173	201	211	230	237	242	247	219
	SE	6.5	7.1	6.8	8.5	7.6	7.7	10.2	3.0

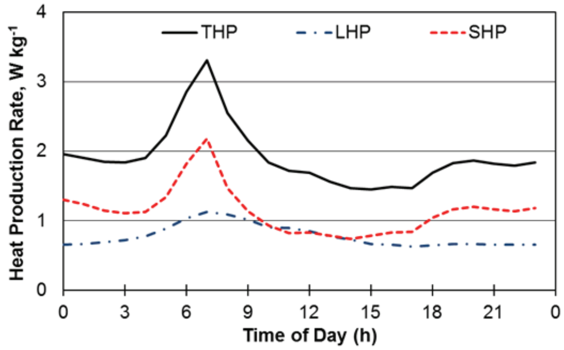


Figure 5. Typical whole-barn diurnal patterns of total, latent, and sensible heat production rates (THP, LHP, and SHP) for the late gestation (LG) barn in winter. Workers were present in the barn from 06:00 to 16:00 h. The sows were fed at 07:00 h.

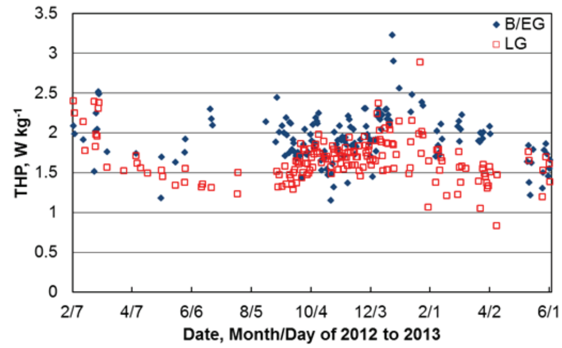


Figure 7. Daily mean total heat production rate (THP) of sows in the breeding and early gestation (B/EG) and late gestation (LG) barns. Sows were in the B/EG barn from day of weaning to day 40 of gestation and in the LG barn from day 40 to day 112 of gestation.

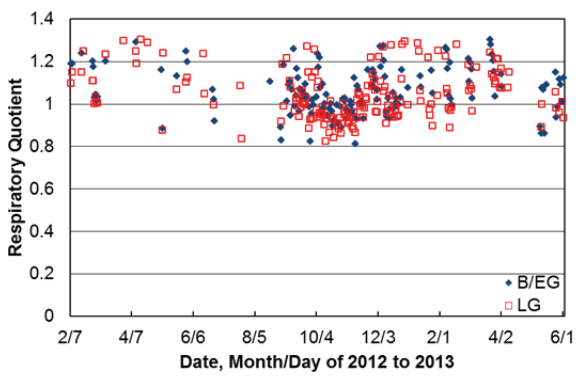


Figure 6. Daily mean respiratory quotient (RQ) of sows in the breeding and early gestation (B/EG) and late gestation (LG) barns. Sows were in the B/EG barn from day of weaning to day 40 of gestation and in the LG barn from day 40 to day 112 of gestation.

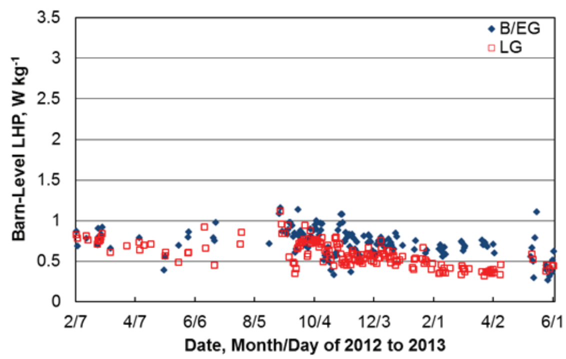


Figure 8. Daily mean barn-level latent heat production rate (LHP) of sows in the breeding and early gestation (B/EG) and late gestation (LG) barns. Sows were in the B/EG barn from day of weaning to day 40 of gestation and in the LG barn from day 40 to day 112 of gestation.

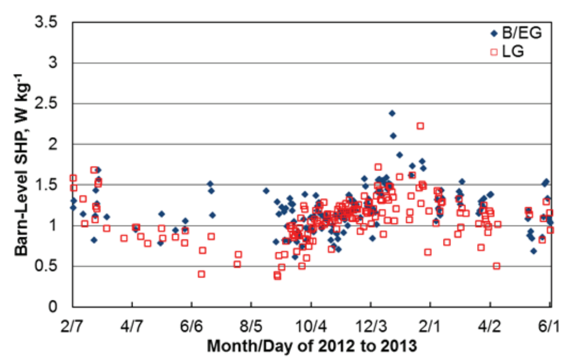


Figure 9. Daily mean barn-level sensible heat production rate (SHP) of sows in the breeding and early gestation (B/EG) and late gestation (LG) barns. Sows were in the B/EG barn from day of weaning to day 40 of gestation and in the LG barn from day 40 to day 112 of gestation.

Standards (ASABE, 2013). The comparison of the results obtained from the current study and the ASABE Standards is discussed later in this article. The impact of barn temperature on HP is shown in figure 10. The trend of increasing SHP with decreasing temperature is noticeable and is consistent with the principles of animal's thermal regulation and heat transfer.

The TWA values for the 20°C temperature category for the B/EG and LG barns (mean ±SE, W kg^{-1}) were 1.89 (±0.04) and 1.57 (±0.02) in THP, 0.74 (±0.01) and 0.57 (±0.01) in LHP, and 1.15 (±0.03) and 1.00 (±0.02) in SHP. The TWA values for the 25°C temperature category for the B/EG and LG barns (mean ±SE, W kg^{-1}) were 1.82 (±0.04) and 1.26 (±0.03) in THP, 1.08 (±0.04) and 0.87 (±0.03) in LHP, and 0.74 (±0.04) and 0.39 (±0.03) in SHP. Overall, for the B/EG barn, the ranges of THP, LHP, and SHP were, respectively, 1.15 to 3.23 W kg^{-1}, 0.32 to 1.15 W kg^{-1}, and 0.62 to 2.38 W kg^{-1}. For the LG barn, the ranges of THP,

Table 3. Summary of diurnal values for total heat production rate (THP), barn-level latent heat production rate (LHP), and barn-level sensible heat production rate (SHP) (W kg^{-1}) and time-weighted average (TWA) values of THP, LHP, SHP, and respiratory quotient (RQ) for the breeding and early gestation (B/EG) barn and the late gestation (LG) barns at barn temperature of 20°C (±2.5°C) and 25°C (±2.5°C).

Production Stage	Barn Temperature		RQ	THP (W kg^{-1})			LHP (W kg^{-1})			SHP (W kg^{-1})		
			TWA	Day	Night	TWA	Day	Night	TWA	Day	Night	TWA
B/EG	20°C (±2.5°C)	Mean	1.07	2.26	1.58	1.89	0.88	0.62	0.74	1.38	0.96	1.15
		SE	0.01	0.04	0.03	0.04	0.01	0.01	0.01	0.04	0.03	0.03
	25°C (±2.5°C)	Mean	1.19	2.12	1.57	1.82	1.16	1.01	1.08	0.96	0.56	0.74
		SE	0.01	0.04	0.03	0.04	0.02	0.05	0.04	0.04	0.04	0. 04
LG	20°C (±2.5°C)	Mean	1.09	1.84	1.35	1.57	0.71	0.46	0.57	1.13	0.89	1.00
		SE	0.01	0.03	0.02	0.02	0.01	0.01	0.01	0.03	0.02	0.02
	25°C (±2.5°C)	Mean	1.22	1.43	1.11	1.26	0.85	0.88	0.87	0.58	0.23	0.39
		SE	0.01	0.04	0.02	0.03	0.03	0.03	0.03	0.04	0.03	0.03

LHP, and SHP were, respectively, 0.83 to 2.89 W kg^{-1}, 0.32 to 1.12 W kg^{-1}, and 0.37 to 2.22 W kg^{-1}.

The reduction in THP from day to night for the 20°C and 25°C temperature categories was, respectively, 30% and 26% for the B/EG barn and 27% and 22% for the LG barn. For the B/EG barn, the barn-level LHP accounted for, on average, 39% of the THP for the 20°C temperature category and 59% of the THP for the 25°C temperature category. For the LG barn, the barn-level LHP accounted for 37% of the THP at 20°C and 69% of the THP at 25°C. The ASABE Standards (ASABE, 2013) report a 34% and 41% partitioning of THP to LHP at 20°C and 25°C, respectively. The higher percentages of THP as LHP observed in the current study were expected because the barn-level LHP was contributed by both the animals and the surroundings (i.e., evaporation of water from the manure and/or drinking water). The higher environmental temperature of 25°C vs. 20°C enhances moisture evaporation from the animals and the surrounding sources.

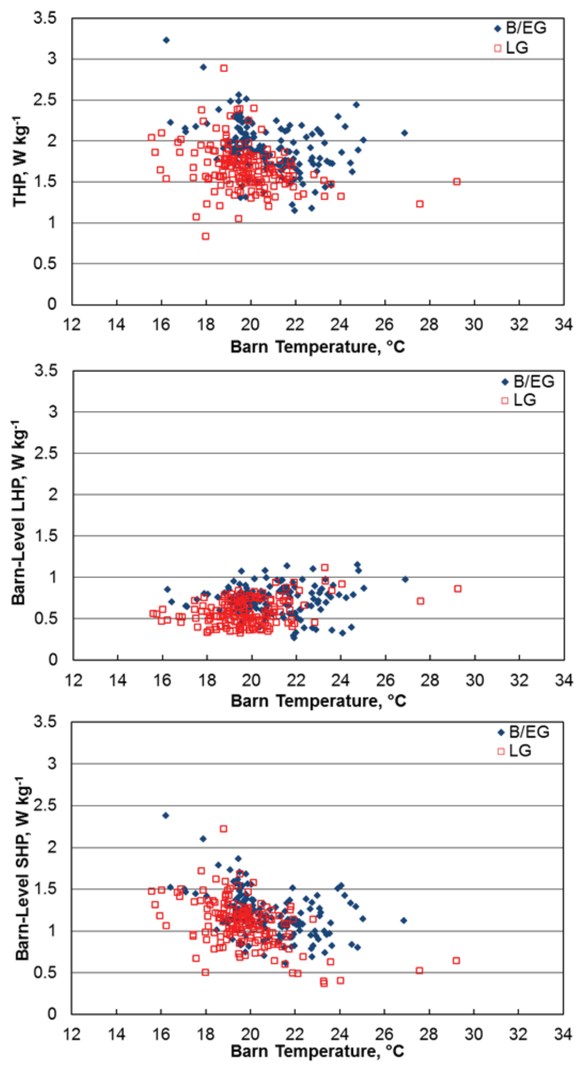


Figure 10. Daily mean total heat production rate (THP), barn-level latent heat production rate (LHP), and barn-level sensible heat production rate (SHP) of sows in the breeding and early gestation (B/EG) and late gestation (LG) barns versus daily mean barn temperature. Sows were in B/EG barn from day of weaning to day 40 of gestation and in the LG barn from day 40 to day 112 of gestation.

HP of Farrowing Rooms F1 and F2

Sample diurnal THP, LHP, and SHP patterns in wintertime are shown in figure 11. The diurnal patterns were not as evident as with sows in the gestation stage. This is likely due to the multiple feeding events of the lactating sow at 00:00, 09:00, 12:00, and 18:00 h and to the frequent feeding activities of the piglets.

RQ ranged from 0.74 to 1.30 (fig. 12) with daily average values (±SE) of 1.06 (±0.04), 1.05 (±0.03), and 1.06 (±0.04) for weeks 0, 1, and 2 of lactation, respectively. Average daily THP, LHP, and SHP over the monitoring period are shown in figures 13, 14, and 15, respectively. In all the figures, the increasing heat production rates during each 18 to 22 day farrowing turn are evident. The trend is better shown in figure 16, where THP, LHP, and SHP are averaged by piglet age (day of farrowing cycle). Overall, THP and SHP increase with piglet age through the first half of the farrowing cycle before leveling off. LHP is not signifi-

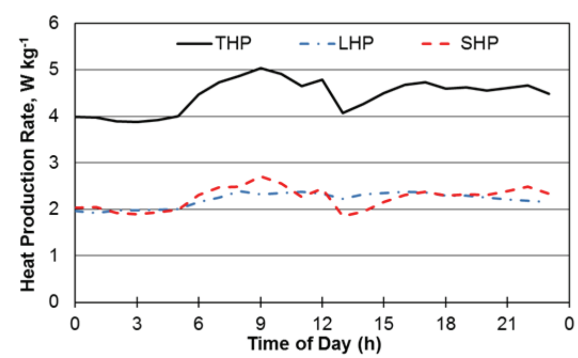


Figure 11. Typical whole-room winter diurnal patterns of total, room-level latent, and room-level sensible heat production rates (THP, LHP, and SHP) for lactating sows and litters. Rooms were occupied by workers from 06:00 to 16:00 h. The sows were fed at 00:00, 09:00, 12:00, and 18:00 h.

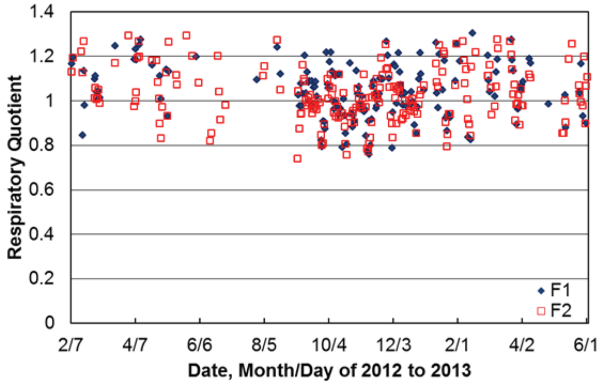


Figure 12. Daily mean respiratory quotient (RQ) of sows and litters in farrowing rooms F1 and F2. The piglets were weaned at 18 to 22 days of age.

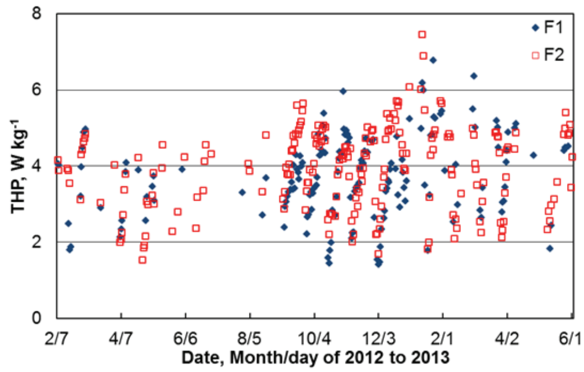


Figure 13. Daily mean total heat production rate (THP) of sows and litters in farrowing rooms F1 and F2. The piglets were weaned at 18 to 22 days of age.

cantly affected by piglet age. This trend is likely due to the rapid growth of piglets and the sows gaining access to almost *ad libitum* feeding after parturition. The results for the lactating sows and litters are summarized in table 4, which includes the daytime, nighttime, and TWA values of THP, LHP, and SHP by production stage. The results are further divided into temperature categories (table 5) for comparing with the ASABE Standards (ASABE, 2013). No consistent pattern of HP versus temperature was apparent. The lack of consistent pattern is likely due to confounding factors among environmental temperature, sow feed intake, piglet age, and different thermal needs between the sows and piglets. Farrowing rooms are typically kept at temperatures in the sow's comfort range of 15.5°C to 18°C, and localized heating is provided for the piglets to maintain a higher-temperature microenvironment of 32°C to 35°C (MWPS, 1983b). This is done both for sow comfort and to reduce room heating costs. The quality of the microenvironment will vary from litter to litter depending on management and location in the room (e.g., near the air inlet). Even if the desired microenvironment is provided, the piglets will not use it constantly, and thus their HP will change to maintain homeostasis (constant core body temperature).

The TWA values for the week 0 stage of lactating sows and litters (mean ±SE, W kg^{-1}) were 3.35 (±0.20) in THP, 1.98 (±0.13) in LHP, and 1.37 (±0.20) in SHP. The TWA values for the week 1 stage of lactating sows and litters

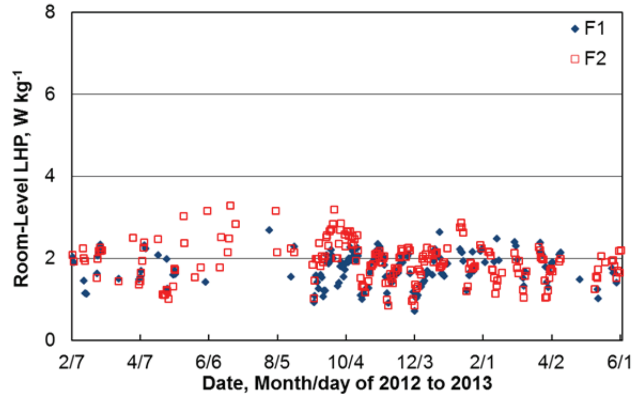


Figure 14. Daily mean room-level latent heat production rate (LHP) of sows and litters in farrowing rooms F1 and F2. The piglets were weaned at 18 to 22 days of age.

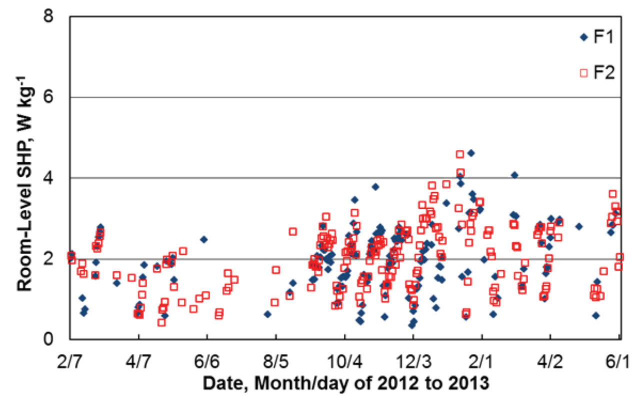


Figure 15. Daily mean room-level sensible heat production rate (SHP) of sows and litters in farrowing rooms F1 and F2. The piglets were weaned at 18 to 22 days of age.

(mean ±SE, W kg^{-1}) were 4.15 (±0.21) in THP, 1.92 (±0.14) in LHP, and 2.23 (±0.24) in SHP. The TWA values for the week 2 stage of lactating sows and litters (mean ±SE, W kg^{-1}) were 4.38 (±0.37) in THP, 1.93 (±0.10) in LHP, and 2.45 (±0.38) in SHP. Overall, the ranges of THP, LHP, and SHP were 1.42 to 7.45 W kg^{-1}, 0.71 to 3.27 W kg^{-1}, and 0.36 to 4.62 W kg^{-1}, respectively.

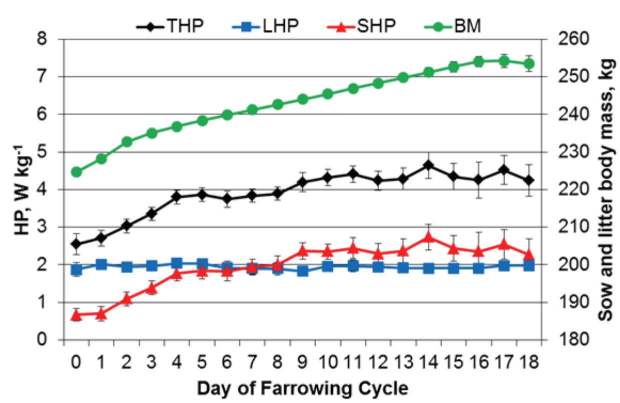


Figure 16. Time-weighted average values of total heat production rate (THP), room-level latent heat production rate (LHP), and room-level sensible heat production rate (SHP) (W kg^{-1}) and average sow and litter body mass (kg) by day of farrowing cycle.

Table 4. Summary of diurnal values for total heat production rate (THP), room-level latent heat production rate (LHP), and room-level sensible heat production rate (SHP) (W kg^{-1}) and time-weighted average (TWA) values of THP, LHP, SHP, and respiratory quotient (RQ) of sows and litters across all room temperatures (20°C to 26°C) for the periods of preparturition, day of birth (day 0) to day 6, day 7 to day 12, and day 13 to day 18 (weaning).

Lactation Stage	Body Mass[a] (kg)	Room Temp. (°C)		RQ	THP (W kg^{-1})			LHP (W kg^{-1})			SHP (W kg^{-1})		
				TWA	Day	Night	TWA	Day	Night	TWA	Day	Night	TWA
Preparturition	222	20-26	Mean	1.05	3.24	2.32	2.74	2.02	1.68	1.83	1.22	0.64	0.91
			SE	0.07	0.38	0.20	0.28	0.18	0.20	0.19	0.29	0.16	0.22
Birth to day 6 (week 0)	235	20-26	Mean	1.06	3.46	3.26	3.35	2.03	1.93	1.98	1.43	1.33	1.37
			SE	0.04	0.21	0.19	0.20	0.14	0.13	0.13	0.21	0.19	0.20
Day 7 to 12 (week 1)	247	20-26	Mean	1.05	4.27	4.05	4.15	2.01	1.84	1.92	2.26	2.21	2.23
			SE	0.03	0.23	0.20	0.21	0.15	0.13	0.14	0.26	0.22	0.24
Day 13 to 18 (week 2)	256	20-26	Mean	1.06	4.57	4.23	4.38	1.97	1.90	1.93	2.60	2.33	2.45
			SE	0.04	0.38	0.37	0.37	0.11	0.09	0.10	0.39	0.38	0.38

[a] Average body mass of sow + litter (kg).

Table 5. Summary of diurnal values for total heat production rate (THP), room-level latent heat production rate (LHP), and room-level sensible heat production rate (SHP) (W kg^{-1}) and time-weighted average (TWA) values of THP, LHP, SHP, and respiratory quotient (RQ) of sows and litters at room temperatures of 20°C to 22°C, 22°C to 24°C, and 24°C to 26°C for the periods of preparturition, day of birth (day 0) to day 6, day 7 to day 12, and day 13 to day 18 (weaning).

Lactation Stage	Body Mass[a] (kg)	Room Temp. (°C)		RQ	THP (W kg^{-1})			LHP (W kg^{-1})			SHP (W kg^{-1})		
				TWA	Day	Night	TWA	Day	Night	TWA	Day	Night	TWA
Preparturition	222	20-22	Mean	1.10	3.19	2.85	3.01	2.16	2.05	2.10	1.03	0.80	0.91
			SE	0.05	0.35	0.33	0.34	0.06	0.11	0.09	0.29	0.22	0.25
		22-24	Mean	0.99	2.77	2.12	2.42	1.85	1.49	1.65	0.92	0.63	0.77
			SE	0.04	0.55	0.17	0.34	0.37	0.16	0.26	0.18	0.01	0.08
		24-26	Mean	1.00	3.38	2.34	2.82	2.78	1.94	2.33	0.60	0.40	0.49
			SE	0.06	0.10	0.37	0.25	0.01	0.30	0.16	0.09	0.07	0.09
Birth to day 6 (week 0)	235	20-22	Mean	1.04	3.81	3.41	3.59	2.10	2.14	2.12	1.71	1.27	1.47
			SE	0.08	0.24	0.25	0.24	0.14	0.20	0.17	0.10	0.05	0.07
		22-24	Mean	1.06	3.32	3.25	3.28	1.96	1.80	1.87	1.36	1.45	1.41
			SE	0.04	0.21	0.20	0.20	0.14	0.12	0.13	0.07	0.08	0.07
		24-26	Mean	1.06	3.12	2.84	2.97	1.75	1.44	1.59	1.37	1.40	1.38
			SE	0.08	0.45	0.32	0.38	0.32	0.20	0.26	0.13	0.12	0.12
Day 7 to 12 (week 1)	247	20-22	Mean	1.03	4.78	4.49	4.62	2.06	1.96	2.01	2.72	2.53	2.61
			SE	0.05	0.36	0.34	0.35	0.18	0.15	0.17	0.18	0.19	0.18
		22-24	Mean	1.06	4.09	3.89	3.98	1.97	1.72	1.83	2.12	2.17	2.15
			SE	0.03	0.23	0.21	0.22	0.14	0.12	0.13	0.09	0.09	0.09
		24-26	Mean	0.64	4.47	4.13	4.28	1.66	1.43	1.54	2.81	2.70	2.74
			SE	0.04	0.34	0.30	0.32	0.30	0.24	0.27	0.04	0.06	0.05
Day 13 to 18 (week 2)	255	20-22	Mean	1.05	4.76	4.32	4.52	2.03	1.96	1.99	2.73	2.36	2.53
			SE	0.04	0.54	0.25	0.38	0.13	0.09	0.11	0.41	0.16	0.27
		22-24	Mean	1.08	4.17	4.12	4.14	1.77	1.71	1.74	2.40	2.41	2.40
			SE	0.04	0.40	0.32	0.36	0.14	0.09	0.11	0.26	0.23	0.25
		24-26	Mean	0.97	5.10	4.66	4.86	1.78	1.42	1.58	3.32	3.24	3.28
			SE	0.04	0.38	0.22	0.29	0.32	0.21	0.26	0.06	0.01	0.03

[a] Average body mass of sow + litter (kg).

The reductions in THP from day to night for the week 0, 1, and 2 stages were 6%, 5%, and 8%, respectively. The lesser THP drop at night as compared to the B/EG and LG barns was attributed to the multiple sow feeding events and frequent feeding of the piglets. The room-level LHP accounted for, on average, 59% of the THP for week 0, 46% for week 1, and 44% for week 2. This decrease of THP:LHP partitioning with piglet age can also be seen from the data in figure 16.

COMPARISON TO ASABE STANDARDS

Table 6 compares the measured heat production rates for the B/EG and LG barns to the ASABE Standards (ASABE, 2013). Overall, the differences in HP at 20°C (±2.5°C) between the current study and the ASABE Standards for the B/EG and LG barns were, respectively, 35% and 12% higher for THP, 72% and 34% higher for barn-level LHP, and 19% and 3% higher for barn-level SHP. The differences in HP at 25°C (±2.5°C) between the current study and the ASABE Standards for the B/EG and LG barns were, respectively, 40% and -3% for THP, 116% and 73% higher for barn-level LHP, and -7% and -51% for barn-level SHP. These changes are on a unit BM basis, and the BM measured in this study (204 kg for B/EG sows and 222 kg for LG sows) was higher than the BM of 180 kg used in the ASABE Standards. Thus, the changes in HP on per sow basis are greater than those on per unit BM basis. The ASABE Standards are also based on direct calorimetry studies of small groups of pigs or individual sows and litters with no manure accumulation in the chamber. While this provides an estimate of the animal HP and MP, it is important to account for facility and management impacts (e.g., stocking density, manure management, and contributions of non-animal sources) in ventilation system design and operation.

Table 6. Comparison of heat and moisture production rates between ASABE Standards and values from the current study for the breeding and early gestation (B/EG) barn and late gestation (LG) barn.[a]

Room Temperature	Source	THP ($W\ kg^{-1}$)	LHP ($W\ kg^{-1}$)	SHP ($W\ kg^{-1}$)
20°C (±2.5°C)	ASABE Standards	1.40	0.43	0.97
	This study, B/EG			
	TWA	1.89	0.74	1.15
	% Difference	35%	72%	19%
	This study, LG			
	TWA	1.57	0.57	1.00
	% Difference	12%	34%	3%
25°C (±2.5°C)	ASABE Standards	1.30	0.5	0.8
	This study, B/EG			
	TWA	1.82	1.08	0.74
	% Difference	40%	116%	-7%
	This study, LG			
	TWA	1.26	0.87	0.39
	% Difference	-3%	73%	-51%

[a] THP = total heat production rate, LHP = barn-level heat production rate, SHP = barn-level sensible heat production rate, and TWA = time-weighted average.

Table 7 compares the HP values of the current study for the farrowing rooms to the ASABE Standards (ASABE, 2013). The comparison is difficult due to differences in BM and farrowing duration. The ASABE Standards list the sow and litter BM ranging from 177 kg at week 0 to 227 kg at week 8. The sow and litter BM in the current study ranged from 222 kg at birth to 257 kg at weaning (day 18). Thus, the HP values during the first week of the farrowing cycle in the current study were compared to the ASABE Standards values for a similar production stage (week 0) and similar sow and litter weight (week 8). The differences during the first week after birth, relative to the ASABE Standards for week 0 and week 8 of farrowing, were, respectively, 29% and -14% for THP, 52% and 10% for barn-level LHP, and 6% and -34% for barn-level SHP. Specifically, the HP values from the current study during the first week are lower than the ASABE Standards values for week 8 (similar weight) but much higher than the ASABE Standards values for week 0 (similar stage). These much higher THP, LHP, and SHP values for similar production stages illustrate the impact of the larger, higher-producing modern sows and litters. It is critical to have accurate standards for housing design to minimize environmental stress so that the animal's productive potential can be better realized.

Table 7. Comparison of heat and moisture production rates between ASABE Standards and values from the current study for lactating sows and litters.[a]

Source	Week of Farrowing Cycle	Body Mass[b] (kg)	Temp. (°C)	THP ($W\ kg^{-1}$)	LHP ($W\ kg^{-1}$)	SHP ($W\ kg^{-1}$)
ASABE Standards						
	0	177	16-27	2.6	1.3	1.3
	8	227	16-27	3.9	1.8	2.1
This study						
	0	235	20-26	3.35	1.98	1.37
	Same stage	% Difference (week 0)		29%	52%	6%
	Similar BM	% Difference (week 8)		-14%	10%	-34%

[a] THP = total heat production rate, LHP = barn-level heat production rate, and SHP = barn-level sensible heat production rate.
[b] Sow + litter body mass (kg).

SUMMARY AND CONCLUSIONS

Swine ventilation design standards are based on heat production (HP) and moisture production (MP) values from studies conducted in the 1950s and 1970s. Literature and standards since those studies have been lacking, especially for the gestation and lactation stages of swine production. In this extensive field study, total heat production rate (THP), barn-level latent heat production rate (LHP), and barn-level sensible heat production rate (SHP) were quantified over a 16-month period at a 4300-sow modern breeding, gestation, and farrowing swine facility using indirect calorimetry. The quantification was made for a breeding and early gestation barn (B/EG, 1800 sows, post-wean to 40 days of pregnancy), a late gestation barn (LG, 1800 sows, 40 to approximately 112 days of pregnancy), and two farrowing rooms (F1 and F2, 40 sows and litters each). The THP, barn-level LHP, and barn-level SHP values were determined for the day, night, and daily time-weighted average (TWA). The following observations and conclusions were made:

For the B/EG barn at 20°C (±2.5°C):

- THP values for the three periods (day, night, and TWA) were, respectively, 2.26, 1.58, and 1.89 $W\ kg^{-1}$.
- Barn-level LHP values for the three periods were 0.88, 0.62, and 0.74 $W\ kg^{-1}$.
- Barn-level SHP values for the three periods were 1.38, 0.96, and 1.15 $W\ kg^{-1}$.
- Day-to-night THP reduction was 30%.
- On TWA basis, LHP accounted for 39% of THP (but 59% at 25°C).

For the LG barn at 20°C (±2.5°C):

- THP values for the three periods (day, night, and TWA) were, respectively, 1.84, 1.35, and 1.57 $W\ kg^{-1}$.
- Barn-level LHP values for the three periods were 0.71, 0.46, and 0.57 $W\ kg^{-1}$.
- Barn-level SHP values for the three periods were 1.13, 0.89, and 1.00 $W\ kg^{-1}$.
- Day-to-night THP reduction was 27%.
- On TWA basis, LHP accounted for 37% of THP (but 69% at 25°C).

For the farrowing rooms at 20°C to 26°C during week 0:

- THP values for the three periods (day, night, and TWA) were, respectively, 3.46, 3.26, and 3.35 $W\ kg^{-1}$.
- Room-level LHP values for the three periods were 2.03, 1.93, and 1.98 $W\ kg^{-1}$.
- Room-level SHP values for the three periods were 1.43, 1.33, and 1.37 $W\ kg^{-1}$.
- Day-to-night THP reduction was 6%.
- On TWA basis, LHP accounted for 59% of THP.

The TWA THP, LHP, and SHP values were, respectively, 35%, 72%, and 19% higher when compared to the ASABE Standards for the B/EG barn at 20°C (±2.5°C) but 12%, 34%, and 3% higher than the ASABE Standards for the LG barn. For the farrowing stage, the THP, LHP, and SHP values were, respectively, 29%, 52%, and 6% different from the ASABE Standards values at a similar production stage (week 0). However, THP, LHP and SHP were, respectively 14% lower, 10% higher, and 34% lower than the ASABE Standards values at similar sow and litter body mass. These data collected in a commercial production operation will contribute to updating of the standards used in the design and operation of ventilation systems for modern swine breeding, gestation, and farrowing facilities.

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